Protection Of Series Capacitor Compensation To Improving Power Capability Of A Transmission Line

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Abstract— This paper introduces the series capacitor compensation method which considers as a leading technique to improve the power system capability; with the analysis of the location of inserted capacitor, degree of compensation, and simulate a protection scheme for the capacitors. A better power transfer capability of an existing transmission line will have a great effect on the overall system and its stability, in addition to its contribution to the economic and environmental sides. The system was established by Power System Computer Aided Design (PSCAD). Protection of series capacitor compensation model consists of a logically designed voltage relay and circuit breakers that are suitable to the system; responding to overvoltage conditions that may occur across series capacitors. The discussed methodology is based on real life data obtained from National Electric Power Company (NEPCO). Simulation results prove that the series capacitor compensation can reduce losses through the transmission line and achieve a higher power delivered to the load.
Keywords-PSCAD; Series Compensation; Power Transmission Lines; Overvoltage; Simulation.

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I. INTRODUCTION

Power systems have been going recently through a lot of studies, research and development accordingly [1], hence are complex systems with high nonlinearity. They need constant planning and control through their main components; generation, transmission, Distribution [2]; the performances of each component play a major role in the overall behavior of the system.

Electricity transmission is the anonymous leader of our modern lifestyle therefore has to be studied carefully to achieve the most satisfying results through reliable paths to accomplish them. A large percent of the power generated today is lost in transit of power, which needs to be reduced. Most of the methods that were attained by specialist for power improvement arose some un-stability and control problems [3,7], until Flexible AC Transmission System (FACTS) deputed in the electricity industry, proving its efficiency in maintaining the stability level and the reliability of the system [8].

One of FACTS technologies is the series capacitor compensation; it is an effective way to amend the performance of Extra High Voltage (EHV) transmission lines, by connecting a capacitor in series with the line at an appropriate location. The principle of series capacitor compensation is to reduce the reactance of the line which decreases the losses and lessens the difference between the angles of the sending and receiving voltage lines [9]. For most power systems the continuity of service requires the maintenance of stability under transient conditions, the series capacitor compensation reduces the transient and steady-state stability limits of transmission systems at unchanged power transfer under the same operation conditions, by decreasing the value of the power angle ‘δ’ [10].

The author in [6] mentioned that the long transmission line especially 482 Km is the optimal length for an efficient and economical applications of series capacitor compensation, which will be used as a reference in the design conducted in this paper. Also, the paper concludes that for greater line loads the series capacitor becomes more efficient to be used than light loads [11]. Not to forger that series compensation method requires control and protection against over voltage and over current.

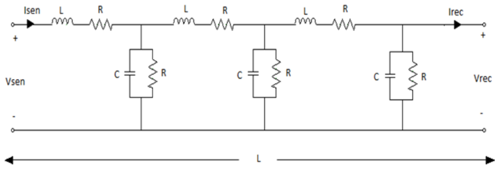

Figure 1. Nominal equivalent circuit of a long transmission line

According to the equivalent network, a matrix form could be found as follow:

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_r \\ I_r \end{bmatrix} \quad (1)$$

$$V_s = A V_r + B I_r$$
$$I_s = C V_r + D I_r \quad (2)$$

Every type is characterized by different ABCD constants, to ensure the correctness of each circuit the results of the models were matched with particle quantities.

The equations for long transmission line model are obtained by finding the ABCD (llow:

$$A = \cosh \gamma \ell \quad (3)$$

$$B = Z_c \sinh \gamma \ell \quad (4)$$

$$C = \frac{1}{Z_c} \sinh \gamma \ell \quad (5)$$

Where;
ℓ = the length of the transmission line.
$\gamma = \sqrt{ZY}$; the propagation constant.
$Z_c = \sqrt{\frac{Z}{Y}}$; the characteristic impedance.

A design of a compensated transmission line using a series capacitor is analyzed and studied with its effect at the same operation conditions for the system. In the following section, a description of the problem and methodology will be held to provide a background on series compensation that will be utilized to enhance the performance of the transmission line using PSCAD. At the analysis and simulation section, the obtained design will be investigated and studied through simulation, additionally, a protection scheme -for the over voltage across series capacitors- was constructed. The last two sections will include the results (including a comparison) and a conclusion, simultaneously.

II. DESIGN AND APPROACH FOR A LONG EHV TRANSMISSION LINE

A. System Description

Figure 2 represents a simplified schematic of a real system in Jordan. Most of the data was collected from NEPCO, whilst the rest were extracted from similar real life systems [12].

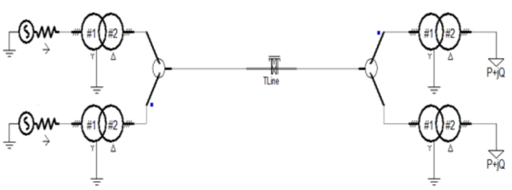

Figure 2. Uncompensated transmission line using PSCAD

A 400 KV, 482 Km, 50 Hz double circuit transmission line with 200 MW load for each circuit was simulated under normal conditions. The transmission line conductors were carried on hexagon tower type; this configuration was obtained from NEPCO. It provides a high surge impedance loading with no need for a very large space compared to other types with light corona losses.

B. Concepts of the Proposed Method

To improve the power and voltage at the receiving end of the transmission line along with the overall stability of the system, the series capacitor compensation was utilized. The active power of the system shown in figure 2, neglecting the resistance value, can be displayed in equation 7.

$$P = \frac{V_{send} * V_{rec}}{X_L} \sin \delta$$

After inserting the capacitors to the lines, the active power will be enhanced. The power equation then can be expressed in equation 8.

$$P = \frac{V_{send} * V_{rec}}{X_L - X_C} \sin \delta \quad (8)$$

Where;

V_{rec} : Receiving end voltage
V_{send} : Sending end voltage
X_L : Inductive reactance of line
X_C : Capacitive reactance of capacitor
δ : Phase shift between sending and receiving end

The degree of compensation 'k' as expressed in equation 9 was used to determine the optimal capacitive reactance; where the degree of compensation is the percentage between inductive reactance of the line (X_L= 612 Ω), as extracted from PSCAD, and its capacitive reactance (X_C). The economical range of k is between 25% to 70% [13]. Two values of k were chosen to acquire the finest value of the capacitance in µF through comparison. In addition, examining their effects on the power value.

$$k = \frac{X_C}{X_L} \quad (9)$$

$$C = \frac{1}{2\pi f X_C} \quad (10)$$

The capacitors can be either mounted on one or both ends of the line which has less installation cost. However, installing those at the midpoint of the transmission line creates less protection problems, consequently making the system more reliable [14]. Thus, the compensation capacitors were decided to be located at the midpoint of the lines in the design, which is also emphasized by a study conducted in [15].

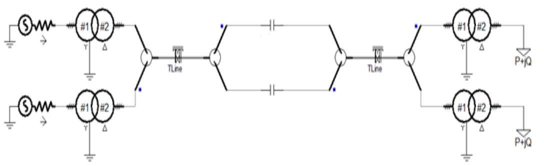

Figure 3. Compensated transmission line using series capacitors

The possibility of faults appearing in the transmission line is higher than any other power system component, because it is exposed to environmental threats such as storms and lightning [16]. The series capacitors were added to the transmission line to improve the power capability and system stability. Despite the improvement, the system faces higher risk of failure due to possible faults on the capacitor itself or by other faults occurring elsewhere in the system.

One of the most common faults that may occur along the grid is the overcurrent faults; they may be caused by excessive circuit load, short circuit or ground faults. When this happens, the transient current cause's high voltage on both ends of the capacitor which may lead to a large voltage drop at the transmission line, thus a protection device is added to the capacitors [17, 19].

III. ANALYSIS AND SIMULATION USING PSCAD

C. Abbreviations and Acronyms Series Compensation Simulation and Results

PSCAD makes it easier to implement power system networks at different operating conditions and simulate the results accurately as if it has been obtained actually from real life applications which save a lot of time, money and it is much safer. Series capacitors were added to the power system design in PSCAD as shown in figure 3 to compensate the power losses in the system; assuming 0.89 lagging PF and 200 MW for each load. Also, both S and Q were calculated accordingly as shown in equations 11 and 12.

$$PF = \frac{P}{S} \qquad (11)$$

$$S = \sqrt{P^2 + Q^2} \qquad (12)$$

After the desired parameters were inserted to the schematic in the PSCAD and the simulation was guaranteed to be working correctly before adding the compensation, the power output and the voltage on the sending end was inspected as shown in figures 4 and 5.

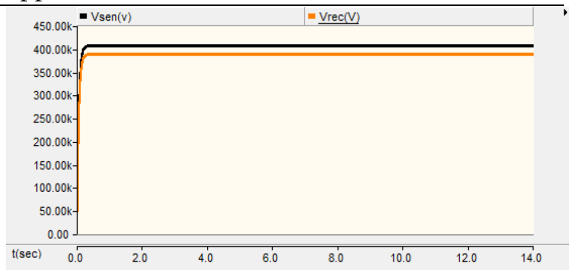

Figure 4. The Voltages on the sending and Receiving before adding the compensation capacitors

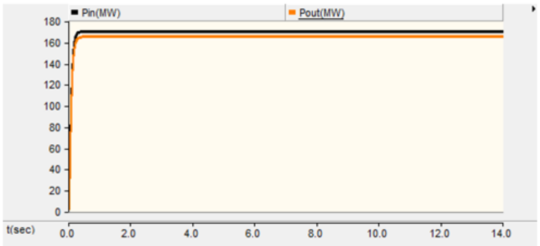

Figure 5. The Power input and output on both ends before adding the compensation capacitors

Furthermore, the compensation capacitors were added in series at the midpoint of the line. The design of the series capacitors was acquired through the inductive reactance X_L of the transmission line and the degree of compensation 'k', referring to equation9,two values of 'k' were chosen for comparison and analysis purposes. Table 1 shows the selected k's and its corresponding capacitance C in µF.

Table (1): the Resultant Capacitance for Different Values of K.

XL= 612 Ω	
K	**C (µF)**
30%	17.34
50%	10.4

The two designs were tested on the simulation respectively to observe the effect of capacitance on the output power and range of compensation each contributes on the overall system. The results can be shown in figures 6, 7, 8, 9.

Table (2) : Discusses the Improvement Power with Different Values of C.

	Vsend (Kv)	Vrec (Kv)	Pin (MW)	Pout (MW)	Qin (MVAR)	Qout (MVAR)
No Capacitor	407.43	388.9	170.2	165.1	-65.8	82.5
C= 17.34 µF	411.5	397.4	187.3	181.5	-79.5	109.8
C= 10.4 µF	415.5	404.2	194.1	187.7	-105.4	113.6

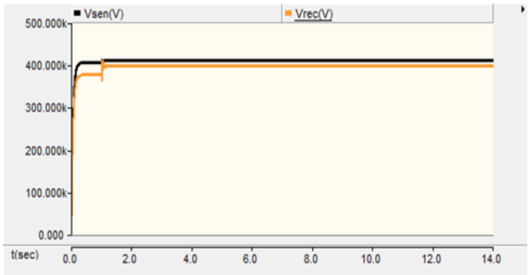

Figure 6. The voltages on the sending and receiving when the degree of compensation is 30% (C=17.34 µf)

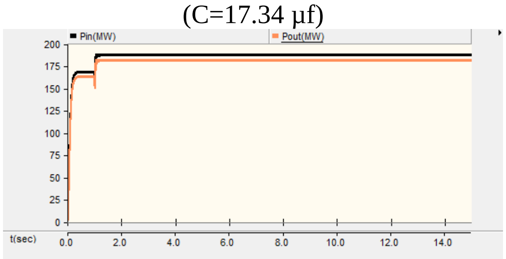

Figure 7. The power input and output when the degree of compensation is 30% (C=17.34 µf)

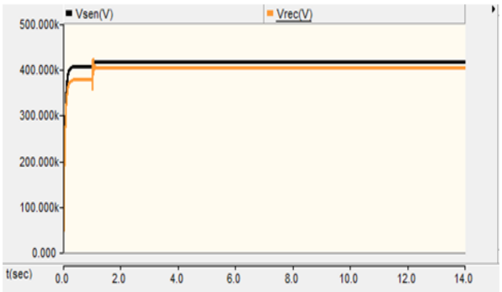

Figure 8. The voltages on the Sending and receiving when the degree of compensation is 50% (C=10.4µF)

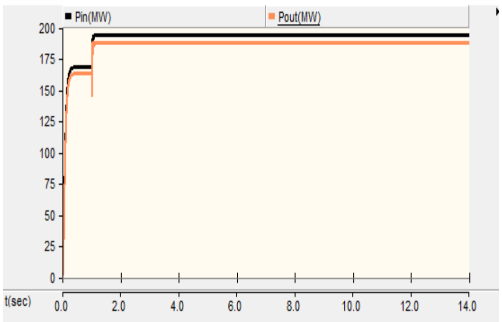

Figure 9. The power input and output when the degree of compensation is 50% (C=10.4 µf)

Adding the series capacitors to the system increases the values of the output power 'Pout' and the voltages at the receiving end 'Vrec'. Furthermore, the capacitance reduction enhances the compensated power at the output, as it was predicted from equation 8 due to the decrease of (XL-Xc), which improves the power transfer capability of the line. Additionally, the Vrec values are improved as indicated in table 2. Moreover, the Vrec increased value affects the reactive power of the load, leading to Qout increase proportionally which can be anticipated from equation 13. Selection of degree of compensation is solely subject to the requirement of the power system function.

$$Q(\text{var}) = I^2 X = \frac{V_{rec}^2}{X}$$

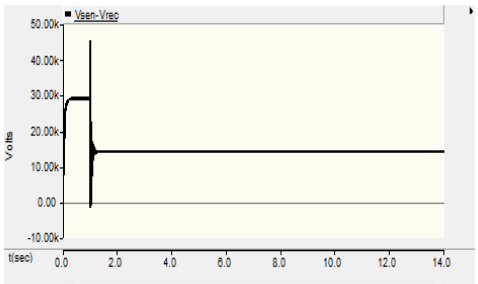

Figure 10. The voltage-drop with C=17.34 µF

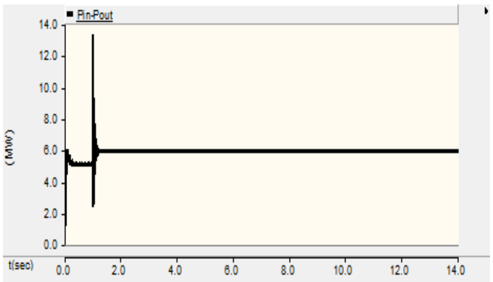

Figure 11. The power difference with C=17.34 µF

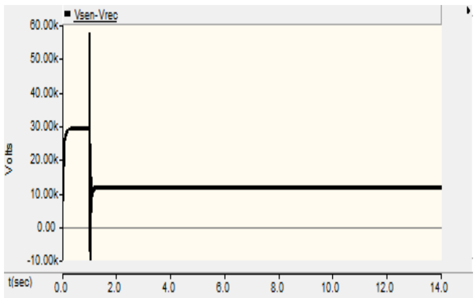

Figure 12. The voltage-drop with C=10.4 µF

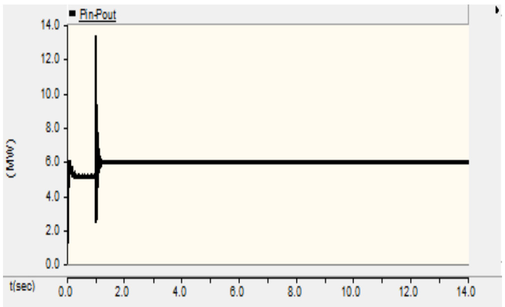

Figure 13. The power difference with C=10.4 µF

The initial voltage drops of 29.3 Kv in the system significantly decreased once the capacitors are added after one second of running the simulation, thus the power transmission capacity increased, as the numbers indicated in the table 3 for a 200 MW power output. Also, the reactive power 'Q' increased with K as indicated in table 2, the current through the lines increased, thus the power losses may have increased respectively.

Table (3) : Voltage Drop and the Percentage of the Power Increased Due to Compensation.

	ΔV (Kv)	ΔP (MW)	Increased percentage of Power
No Capacitor	29.3	5.1	-
C=17.34 μF	14.1	5.9	9.93%
C=10.4 μF	11.3	6.4	13.45%

D. Protection Simulation

When the voltage drop across the series capacitors arises, this exposes them to an overvoltage which may damage them, consequently could lead to open circuit faults in the system. A protection system is required to be added across them. Accordingly, a logical design was built up to cover the absences of overvoltage relay in the PSCAD.

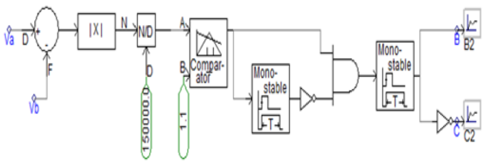

Figure 15. Logical protection scheme in PSCAD

At normal operational conditions, the voltage drop across the capacitors 'ΔV1' needs to be detected under consideration of the safety factor of 1.1 (ΔV1*1.1=15000) to be set as a reference value to the design. Moreover, continuous readings of the voltage drop are obtained and send to the relay where they are divided by 15000 illustrated in figure 18. Then, the result enters the comparator which indicates if there is an overvoltage through comparing the instantaneous ration with the safety factor 1.1.

A Mono-stable integrated with a logical inverter shown in figure 16 is used as a delay function, this delay is essential; if faults occur in a short duration up to 0.06 seconds and can recover with no interference such as transient responses, the overvoltage relay will not be activated. If it exceeds the 0.06 seconds the relay will pass the signal to the next stage, which is dedicated to holding the value for (17 sec) until the problem is solved, because of the sinusoidal nature of the voltage signal.

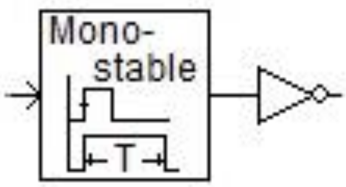

Figure 16. Mono-stable integrated with a logical inverter stage in the overvoltage relay

In each circuit, the capacitors are surrounded by two CB's (normally closed) on both sides, and one CB (normally open) in parallel with each capacitor. When the relay gives the signal, the CB's will trip accordingly, causing a short circuit bypassing the capacitors, thus protecting the capacitor from any damage, and insuring the continuity of service.

The protection system was tested at k=50% C=10.7 uF to observe the behavior of the CB's responding to a fault. Initially the fault was injected on the generation side of the upper circuit of the power system as shown in Figure 20. Consequently, the CB's across the series capacitor sides tripped due to the overvoltage relay allowing the current to pass through a short circuit forward the load. Noticing that the CB's across the transformer also tripped under the influence of an inverse current relay which was added to the system to insure to simulate the behavior of a real life power system. The second circuit will continue to work normally feeding both loads.

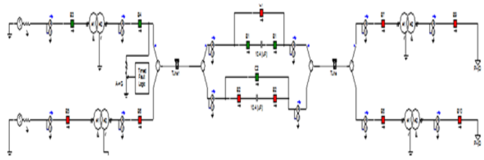

Figure 17. Fault inserted on the generation side and its effect on the power system

Then after, a fault on the load side of the upper circuit was injected to spot its impact on the system. Furthermore, the designed relay detected the overvoltage on the series capacitors causing the CB's to trip successfully. Moreover, it can be noticed that the CB's on the load side also tripped due to the inverse current relay protection. Both generators feed the second circuit load as can be seen below in Figure 17.

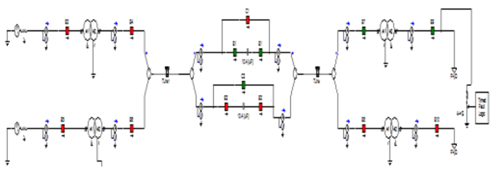

Figure 18. Fault inserted on the load side and its effect on the power system.

IV. CONCLUSION

Adding a series capacitor to the transmission line increases power transfer capability and improves the stability of the overall system although it may cause fault problems that can be solved and controlled using a certain protection scheme designed with logical circuits due to unavailability of a voltage relay in PSCAD; the scheme can control the tripping time, safety factor, starting and delay time. This method applied to a simulated transmission line can be applicable to any existing practical transmission line.

REFERENCES

[1]. Lv Zhou, Akshya Swain, Prem K Naik, Faizal Hafiz and Nirmal-Kumar C Nair, “Optimum Design of Series Compensation to, Improve Power System Transient Stability Using, DFQL and PSO Based Controllers”, Department of Electrical & Computer Engineering,The University of Auckland, New Zealand, 2017.

[2]. Robert H. Lassetser, “Distributed Generation”, Department of Electrical and computer Engineering. University of Wisconsin-Madison, September 4, 2003.

[3]. H. D. Al-Majali and S. M. Al-Dhalaan, “Transient of modified HVDC converters,” *Electr. Power Syst. Res.*, vol. 77, no. 10, pp. 1329–1336, 2007

[4]. H. D. Al-Majali, "Voltage control of modified series-connected HVDC bridges," *Electric power systems research*, vol. 43, no. 1, pp. 37-44, 1997.

[5]. H. D. Al-Majali, "Voltage control of modified series-connected HVDC bridges using GTO thyristor by-pass valves," *Electric power systems research*, vol. 49, no. 2, pp. 79-86, 1999.

[6]. H. D. Al-Majali, "Abnormal Harmonics Generated by Modified HVDC Converter," *Electr. Power Components Syst.*, vol. 35, no. 6, pp. 639–654, 2007.

[7]. H. D. Al-Majali, and D. O’Kelly, "Control of an HVDC converter using by-pass valves,"*25th UPEC. Robert Gordon’s Institute of Technology, Aberdeen, UK,* vol. 1, pp. 325-328, 1990.

[8]. Dheeman Chatterjee,” Transient stability assesment of power systems containing series and shunt compensation”, IEEE Transactions on Power Systems 22 (3), 1210-1220, Aug 2007

[9]. Qisheng Liu, Jiawen Yu, He Chen, and Van Qin, “Studies on Series Compensation of UHV Transmission Line”, Hangzhou, China, 2010.

[10]. J. W. Butler, J. E. Paul and T. W. Schroeder, “Steady-State and Transient Stability Analysis of Series Capacitors in Long Transmission Lines”, AIEE TRANSACTIONS, pages 58–65, February,1943

[11]. John G. Holm, “stablty study of A-C power-transmission system”, AlEE TRANSACTIONS, volume 61, 1942, pages 893-905.

[12]. William D. Stevenson, Jr, "Elements of power system analysis", 4th ed, New York, USA,[table A.1], pp.364-365.

[13]. Hadi Saadat, “Power System Analysis ”, New York, USA, pp. 126, pp. 159-160 and pp. 168-170, 2002.

[14]. Héctor J. Altuve, Joseph B. Mooney, and George E. Alexander,” Advances in Series-Compensated Line Protection”, 63rd Annual Georgia Tech Protective Relaying Conference Atlanta, Georgia, 2009.

[15]. R. Kingston, N. Holmberg, J. Kotek and Y. Baghzouz, “ Series Capacitor Placement on Transmission Lines with Slightly Distored Currents”, Proc. IEEE Power Engineering Society Transmission and Distribution Conference, 1994.

[16]. K.K Ram, S. Nirmala, K. Ramesh and D.N. Vishwakarma. “An overview – Protection of Transmission line Using Artificial Intelligence Techniques”, International Journal of Engineering Research & Technology (IJERT), vol. 2, no. 1, January 2013, pp. 1-9.

[17]. Himanshu M. Joshi and Nishant H. Kothari, “A review on Series Compensation of Transmission Lines and Its Impact on Performance of Transmission Lines”, Rajkot, India, 2014.

[18].] N. Kang, J. Chen and Y. Liao, “ A Fault-location Algorith for Series- Compensated Double-Circuit Transmission Lines Using the Distributed Parameter Line Model”, IEEE Transaction of Power Delivery, vol. 30, no.1, pp. 360-367, 2015.

[19].] Moeini. A and Kamwa. I, “Analytical Concept for Reactive Power Based Primary Frequency Control in Power Systems”, IEEE Transaction on Power Systems, vol.31, no.6, pp. 4217-4230, 2016.

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